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Human Exploration and Settlement of the Moon Using LUNOX-Augmented NTR Propulsion

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HUMAN EXPLORATION AND SETTLEMENT OF THE MOON
USING LUNOX-AUGMENTED NTR PROPULSION

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Abstract

An innovative trimodal nuclear thermal rocket (NTR) concept is described which combines conventional liquid hydrogen (LH_2)-cooled NTR, Brayton cycle power generation and supersonic combustion ramjet (scramjet) technologies. Known as the liquid oxygen (LOX)-augmented NTR (LANTR), this concept utilizes the large divergent section of the NTR nozzle as an "afterburner" into which LOX is injected and supersonically combusted with nuclear preheated hydrogen emerging from the LANTR's choked sonic throat--"scramjet propulsion in reverse." By varying the oxygen-to-hydrogen mixture ratio (MR), the LANTR can operate over a wide range of thrust and specific impulse (Isp) values while the reactor core power level remains relatively constant. As the MR varies from zero to seven, the thrust-to-weight ratio for a 15 thousand pound force (klbf) NTR increases by ~440%--from 3 to 13--while the Isp decreases by only ~45%--from 940 to 515 seconds. This thrust augmentation feature of the LANTR means that "big engine" performance can be obtained using smaller, more affordable, easier to test NTR engines. "Reoxidizing" the bipropellant LANTR system in low lunar orbit (LLO) with high density "lunar-derived" LOX (LUNOX) enables a reusable, reduced size and mass lunar transfer vehicle (LTV) which can be deployed and resupplied using two 66 t-class Shuttle-derived launch vehicles. The reusable LANTR can also transport 200 to 300% more payload on each piloted round trip mission than an expendable "all LH_2" NTR system. As initial outposts grow to eventual lunar settlements and LUNOX production capacity increases, the LANTR concept can also enable a rapid "commuter" shuttle capable of 36 to 24 hour "one way" trips to the Moon and back with reasonable size vehicles and initial mass in low Earth orbit (IMLEO) requirements.

INTRODUCTION

Various lunar mission profiles and space transportation system (LTS) options have been examined over the last seven years. In its "90 Day Study Report" (NASA 1989), NASA selected a lunar orbit rendezvous (LOR) mission profile and a LTS consisting of a space-based LTV operating between low Earth orbit (LEO) and LLO, and a lunar landing vehicle (LLV) for transportation from LLO to the lunar surface and back (Priest and Woodcock 1990). The partially reusable LTV employed aerobraking for capture into LEO and was refurbished after each mission at a LEO transportation node assumed to be a growth version of the space station. A cargo version of the current Space Shuttle (Shuttle C) or an "in-line" Shuttle-derived vehicle (SDV) was also baselined for Earth-to-orbit launch (see Figure 1). In the subsequent Synthesis Group report (Synthesis Group 1991), the concepts of aerobraking and vehicle reusability were abandoned for safety and cost considerations, in favor of an all propulsive, expendable mission mode. A dual launch Earth orbit rendezvous and dock (EOR&D) scenario was adopted for vehicle assembly and a "direct capsule reentry" at Earth return eliminated the need for a LEO transportation node.

Concurrent with aerobraking and chemical propulsion concept studies, the benefits of a NTR-based LTS was examined at the NASA Lewis Research Center (Borowski 1991). With its factor of two advantage in Isp over chemical propulsion and its attractive engine thrust-to-weight ratio (~3-10), NTR propulsion enabled a fully reusable, all propulsive LTS for less IMLEO than even the partially reusable, aerobraked chemical systems baselined in the 90 Day Study. Reusability, however, required a LEO propellant depot or expendable propellant tanker for LH_2 refueling. The use of low density LH_2 also increased the NTR LTV size and necessitated larger diameter payload shrouds (e.g., Shuttle C-Block II in Figure 1) to launch the necessary vehicle components.

Oxygen's abundance (~45% by mass) in the lunar regolith (Sullivan and McKay 1991) represents a valuable resource which can be exploited for lunar base development. By providing LUNOX for power, life support and propulsion systems, dramatic reductions in IMLEO and lunar base operating costs are predicted. The LANTR
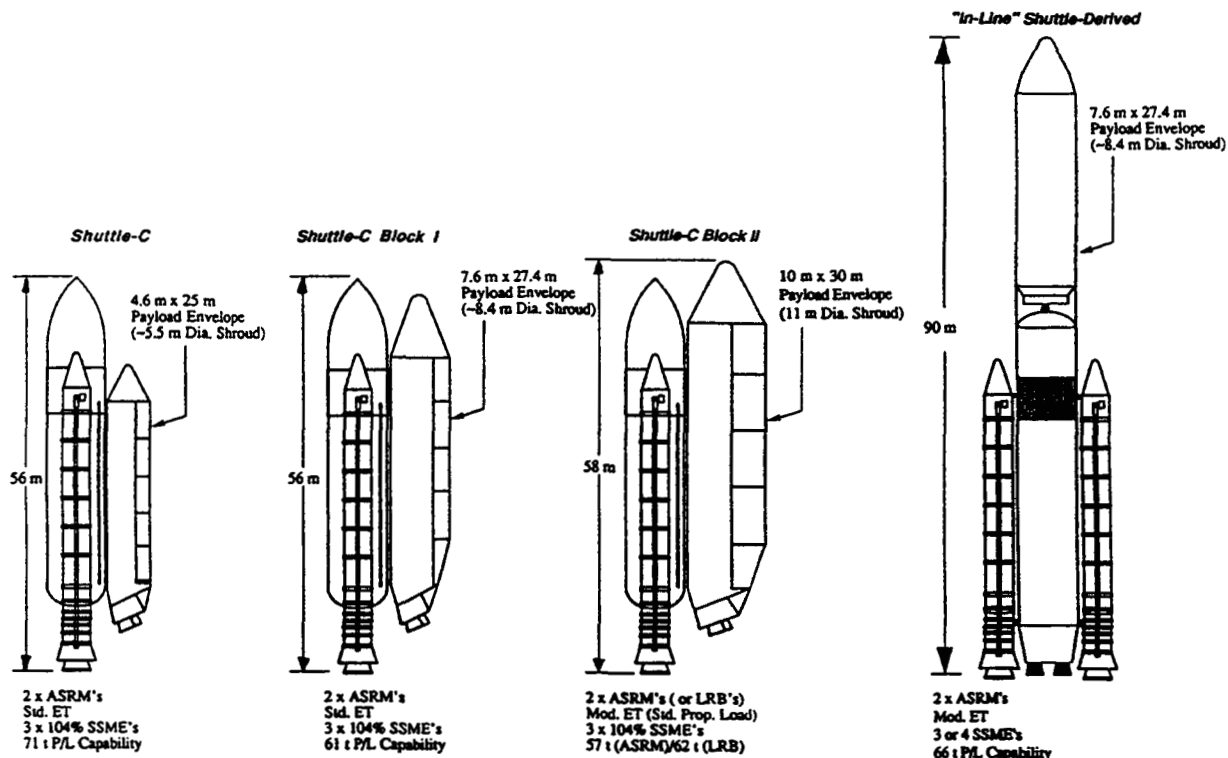
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FIGURE 1.   Shuttle-Based Options for Lunar Launch Vehicles.

concept described here leverages the high Isp capability of the NTR and the availability of LUNOX and provides the basis for a revolutionary LTS architecture (Borowski et al. 1994) possessing a variety of engine, vehicle and mission benefits. The implementation strategy for this architecture uses expendable "all LH$_2$" NTR systems initially to maximize the surface landed payload per mission while minimizing IMLEO requirements. This approach allows us to use near term Shuttle C or SDV technology which analysis (Rutledge 1994) indicates would be cheaper to develop and operate than the reusable, reduced-payload-capability, Single Stage to Orbit (SSTO) vehicle. The increased payload delivered on each expendable NTR flight is also leveraged to land surface systems dedicated to lunar resource utilization. Our intent here is to use LUNOX to "reoxidize" LLVs and LTVs at the earliest possible opportunity (ExPO 1992, Joosten and Guerra 1993) and to then transition to a reusable LTS architecture to minimize recurring costs to the point where commercialization and human settlement of the Moon can become practical.

THE LOX-AUGMENTED NTR CONCEPT

The trimodal LANTR engine, shown in Figure 2, operates in three different modes: thrust with hydrogen propellant, electric power only, and thrust with oxygen and hydrogen propellants. The LANTR contains a reactor and nozzle to heat and expand propellant, hydrogen and oxygen feed systems with autogenous gas bleed for tank pressurization, and a closed Brayton power cycle for engine cooldown, deep throttling, and electric power generation. The hydrogen feed system is powered by engine waste heat using a highly recuperated topping cycle which enables the engine to run at a nozzle inlet pressure of 2000 psia. This and the fact that the recuperator also doubles as the reactor's cooled gamma radiation shield reduces engine size and mass. The hydrogen system generates electricity by bleeding through the Brayton cycle turbine, which drives an electric motor/generator and a compressor. The latter is used during closed loop and low power operation for hydrogen gas circulation, reactor cooldown, and electric power generation. An "on-off" valve, located in the subsonic rocket nozzle, is shut during closed loop modes of operation to prevent leakage of hydrogen working fluid to space, and opened to the hot hydrogen exhaust during thrust mode operation. Waste heat is rejected to space using a combination of nozzle and heat pipe radiators (see Figure 2).

During bipropellant operation the oxygen feed system uses a topping cycle powered by an oxidizer-rich preburner. Downstream nozzle injection isolates the reactor core from oxygen damage provided the throat retains choked flow.
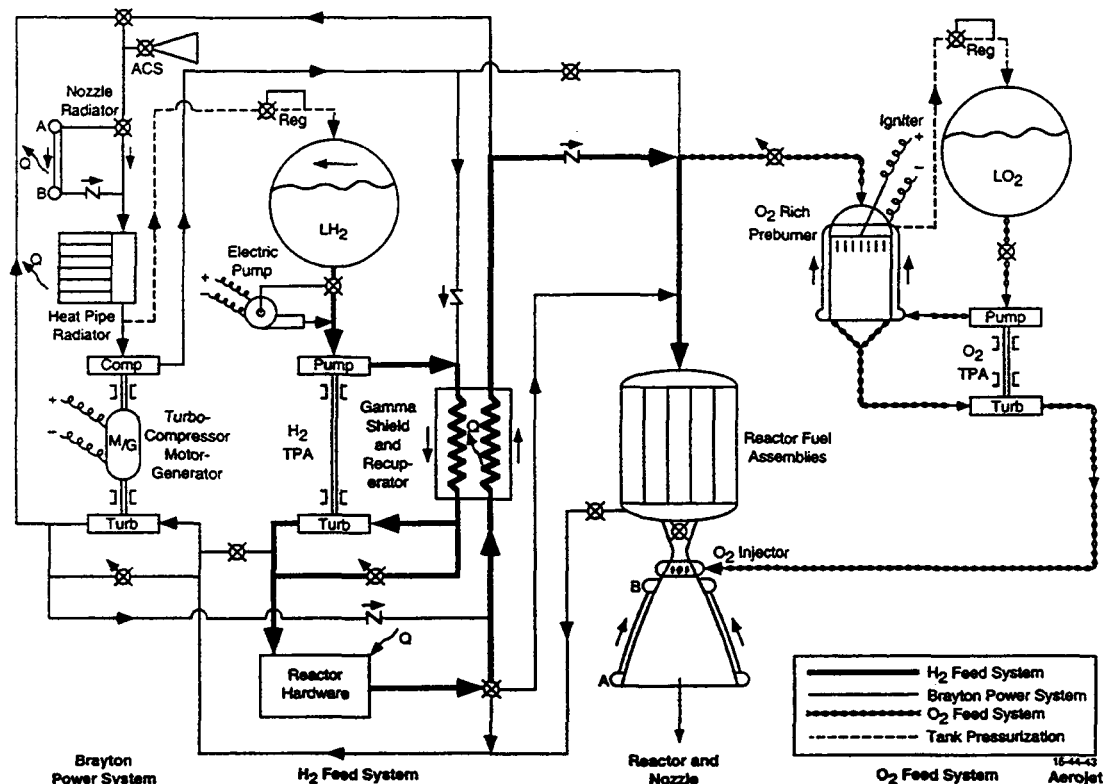
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FIGURE 2.   Flow Schematic of LOX-Augmented NTR Engine.

This condition is satisfied using a "cascade" scramjet injector concept developed by Aerojet which controls oxygen addition and heat release profiles (via staged injection) to keep the flow supersonic (Borowski et al. 1994). It also increases penetration, mixing and combustion of the oxygen injectant in the supersonic hydrogen flow while minimizing shock losses and high heat flux regions (hot spots), thereby maximizing engine performance and life. The high reactor outlet pressure of the LANTR (~2000 psia) also enables high area ratio nozzles ($\varepsilon = 500$ to 1), important for combustion efficiency, at reasonable size and mass.

An extremely versatile feature of the LANTR is its ability to operate over a wide range of thrust and Isp values by varying the engine's oxygen-to-hydrogen (O/H) mixture ratio (MR). Figures 3 and 4 show the variation of engine thrust-to-weight (T/W$_e$) ratio, bipropellant tank fraction and Isp with MR. As the MR varies from zero to seven, the T/W$_e$ ratio for a 15 klbf LANTR increases by ~440%--from ~3 to 13. This thrust augmentation feature means that small LH$_2$-cooled NTR engines can be developed and tested on Earth in affordable "contained" facilities and then operated in space in the augmented high thrust mode to reduce Earth escape gravity losses and eliminate the need for perigee propulsion. The bipropellant tank fraction also decreases with increasing MR, dropping by ~540%--from 14% to ~2.6% at MR = 7, while the Isp degrades by only ~45%--from 940 to 515 seconds. The LANTR concept provides the space vehicle designer substantial flexibility to accommodate a wide variety of mission needs, as well as, volume- and/or mass-constrained launch vehicle designs.

LUNAR MISSION SCENARIOS/VEHICLE DESCRIPTIONS

The reference lunar architecture includes both cargo and piloted lander missions conducted initially in an expendable mode. Key ground rules and assumptions associated with the mission scenario and transportation system are summarized in Tables 1 and 2, respectively. The LTS elements for each mission are launched into LEO using two "in-line" SDVs, each with a lift capability of ~66 t. Figure 5 illustrates the chemical propulsion version of the piloted mission which assumes a capsule reentry at mission end. The first SDV flight launches the LOX/LH$_2$-fueled trans-lunar injection (TLI) stage. The second SDV flight launches the lunar orbit insertion/trans-Earth injection
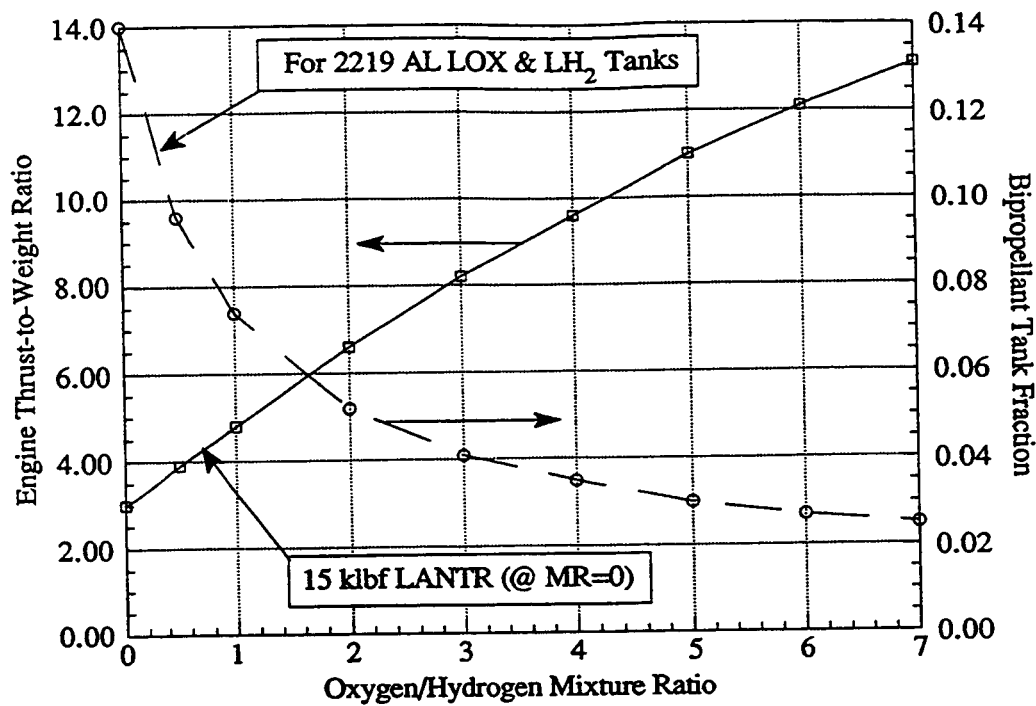
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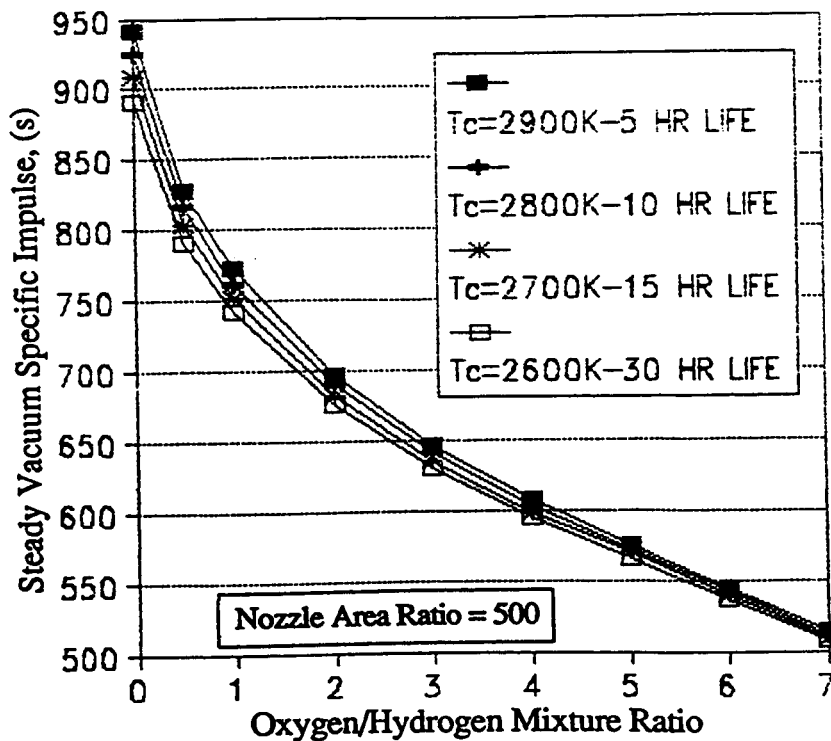**FIGURE 3.** Variation of Engine Thrust-to-Weight Ratio & Bipropellant Tank Fraction With O/H Mixture Ratio.

FIGURE 4. Variation of Specific Impulse With O/H Mixture Ratio.

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TABLE 1.   Reference Lunar Mission Ground Rules and Assumptions.

• Payload Outbound:		9.9 t	LTV crew module
		0.8 t	Crew (4) and suits
		5.0-10.0 t	Lunar surface payload
		5.0 t	LLV crew module
		35.7-46.0 t	"Wet" LLV stage
• Payload Inbound:		9.9 t	LTV crew module
		0.8 t	Crew (4) and suits
		0.5 t	Lunar samples
• Parking Orbits:		407 km	Circular (Earth departure)
		300 km	Circular (lunar arrival/departure)

- Trans-lunar injection ΔV assumed to be 3100 m/s + g-losses
- Lunar orbit capture/trans-Earth injection ΔV's assumed to be 915 m/s
- Earth return: Direct capsule entry
- Earth gravity assist disposal ΔV assumed to be 194 m/s (for NTR system)
- Mission duration: 54 days* (2 in LEO, 7 in transit, 45 days at Moon)
- HLLV type/payload capability: "in-line" SDV/66 t to 407 km circular
- LTV assembly scenario: 2 HLLV launches with EOR&D (IMLEO < 132 t)

* Chemical TLI and NTR "core" stages in LEO for 30 days prior to second HLLV launch

TABLE 2.   Lunar NTR Transportation System Assumptions.

• NTR System:	Propellants	= Cryogenic hydrogen and oxygen
	Isp	= 940 s (@ O/F MR = 0.0 / LH$_2$ only)
		= 647 s (@ O/F MR = 3.0)
		= 514 s (@ O/F MR = 7.0)
	External Shield Mass	= 2.84 kg/MWt of reactor power
	Flight Reserve	= 1% of total tank capacity
	Residuals	= 1.5% of total tank capacity
	Cooldown (effective)	= 3% of usable LH$_2$ propellant
• RCS System:	Propellant	= N$_2$O$_4$/MMH
	Isp	= 320 s
	Tankage	= 5% of total RCS propellants
• Cryogenic Tankage:	Material	= "Weldalite" Al/Li alloy
	Diameter	= 4.6 - 10.0 m
	Geometry	= Cylindrical tank with $\sqrt{2}/2$ domes
	Insulation	= 2 inches MLI + micrometeoroid debris shield
	LH$_2$/LOX Boiloff*	= 1.31/2.44 kg/m²/month (LEO @ ~ 240 K)
		= 0.56/0% kg/m²/month (in-space @ ~ 172 K)
		= 1.92/3.68 kg/m²/month (LLO @ ~ 272 K)
• Contingency:	Engines & external shields	= 15%
	All other dry masses	= 15%

* Assumes 3 x "Lockheed Eqn" heat flux estimates for MLI Δt ~ 2 inches

(LOI/TEI) stage, the piloted crew module and the LLV and its surface payload. The LTS elements are then assembled into an integrated vehicle via an EOR&D maneuver (see Figures 5 and 6a). After 2 days in LEO for system checkout, the TLI stage uses its 5 RL10-derivative engines (with Isp ~465 s) to inject the piloted LOI/TEI stage and lander elements to the Moon and is then jettisoned. Three RL10 engines are used in the LOI/TEI stage to capture into and depart form lunar orbit after a 45 Earth day landing mission (covering a lunar day, night, day cycle). The LLV uses 5 throttleable RL10s and delivers 5 t of surface payload on the piloted missions. On cargo missions, the 5 t crew cab is removed and 28 t payloads can be delivered on "one way" trips to the lunar surface.

Expendable NTR System Performance

The relative size and mass of the chemical and NTR-powered piloted LTVs examined in this study are shown in Figure 6. The expendable "all LH$_2$" NTR vehicle is a "2 tank" configuration (Figure 6b) also launched using two SDVs. The first SDV flight delivers the "core" stage which is powered by two 15 klbf bimodal NTRs each capable of generating ~15 kWe of electrical power using a hydrogen working fluid, closed Brayton cycle power conversion unit (CBC/PCU). The bimodal design considered here was developed by a joint US/CIS (Commonwealth of Independent States) team under NASA funding (Culver et al. 1994). The CBC/PCU is enclosed within the conical extension of the stage thrust structure which also provides support for a 24 m^2 heat pipe radiator required for the two engine system. Additional radiator surface area (~13 m^2) is provided by the bimodal NTR's large expansion ratio nozzles. Other "core" stage elements include: (1) two external radiation shields for crew protection; (2) a 7.6 m diameter by 17.5 m long LH$_2$ tank; (3) a forward cylindrical adaptor housing the RCS system, avionics and auxiliary power, and docking system; and (4) forward and aft cylindrical band skirts. The mass of the "dry" core stage, and its RCS and LH$_2$ propellant loads are 16.0, 0.4, and 49.3 t, respectively, for a total mass at liftoff of ~65.7 t. The "core" stage total length is a little over 24 m, well within the 27.4 m payload length limit of the SDV/Shuttle C-Block I launch vehicles (see Figure 1).

The second SDV launch, 30 days later, delivers another 65.7 t to LEO consisting of a second, smaller LH$_2$ tank with its "conical" core stage adaptor, the piloted LTV crew module and crew, and the LLV and its payload. The "in-line" LH$_2$ tank is 4.6 m in diameter and 9.0 m long and has a 9 t LH$_2$ propellant capacity. After rendezvous and docking, the 46 m long NTR LTV and its payload depart for the Moon. A "single burn" Earth departure scenario is
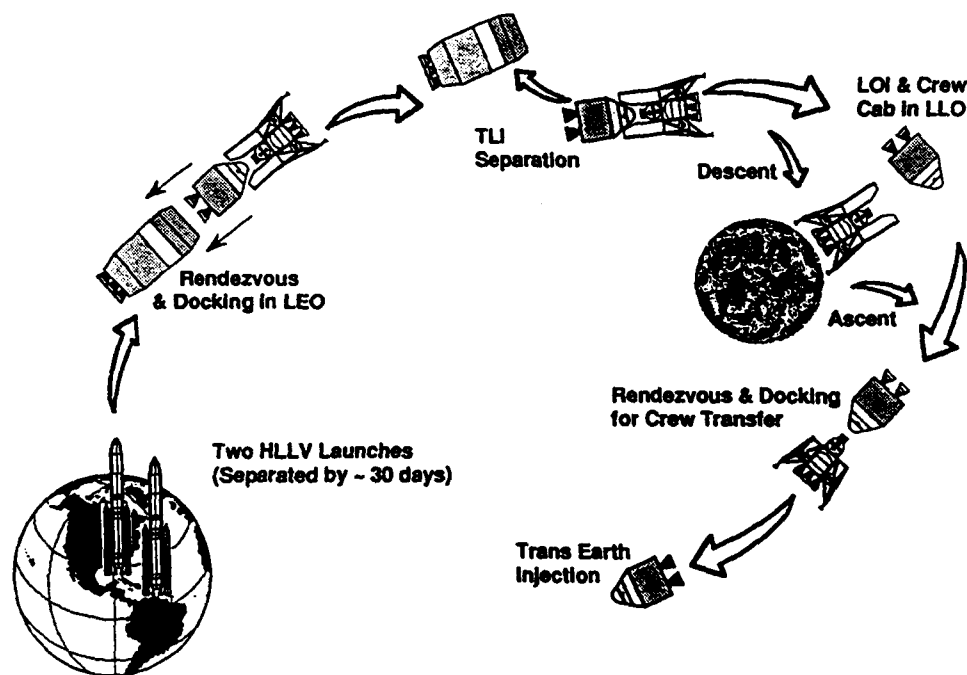

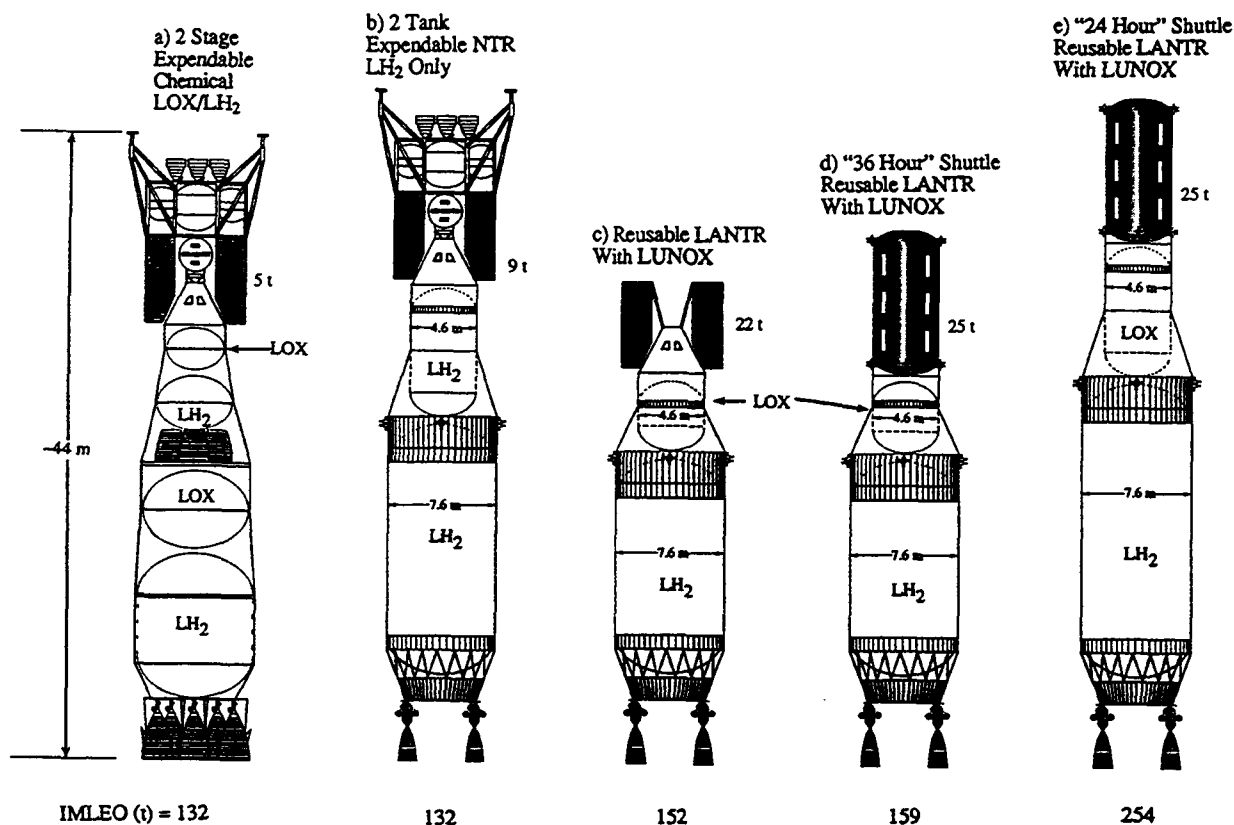FIGURE 5.   Reference Piloted Lunar Mission Scenario Using Two SDV Launches.

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FIGURE 6. Relative Size/Mass of Chemical & NTR Vehicles With & Without LOX Augmentation.

assumed and includes gravity losses of ~392 m/s. The TLI burn duration is ~47.5 minutes and the total mission burn time for the two 15 klbf NTRs is ~61.4 minutes.

Because of its high Isp (~940 s), the NTR-powered piloted LTV can transport a larger LLV to LLO capable of landing 9 t of surface payload--an 80% increase over the chemical LTV system for the same IMLEO. On cargo missions, payloads on the order of 34 t can be delivered to the lunar surface by the chemical LLV representing a 378% increase over the piloted mission mode. The NTR system also appears to be less complex with fewer stages and engines. After LOR and docking of the piloted LLV with the NTR LTV, and transfer of crew and lunar samples to the LTV crew module, the LLV is jettisoned and the core stage performs a TEI burn to return to Earth. Following separation of the LTV crew cab for its ballistic reentry to Earth, the NTR LTV performs a final small (~194 m/s) Earth perigee burn resulting in "long-term disposal" of the stage into heliocentric space. This same disposal scenario is also repeated on cargo missions.

LANTR System Performance with LUNOX

Once LUNOX becomes available in LLO for "reoxidizing" the LANTR LTV, monopropellant NTRs would be outfitted with an oxygen propellant module, feed system and afterburner nozzle for bipropellant operation. The lunar mission scenario now transitions from an expendable to a "reusable" mode with the piloted LANTR system capable of delivering ~27 t of cargo and Earth-supplied LH_2 into LLO. Crew and cargo are transported to the lunar surface by reusable LLVs that are now maintained and refueled at the lunar outpost. In the reusable mode, however, the LLV has a reduced cargo delivery capability because the lander's tankage and propellant load (~22.3 t of LOX/LH_2 at MR = 6) was sized to deliver ~9 t of surface payload on the initial expendable piloted missions. When the LLV (which has a "dry" mass of 11.4 t including its 5 t crew cab) operates from the lunar outpost, ~11.5 t of propellant is used in ascending to LLO for rendezvous with the LTV. This estimate assumes an ascent ΔV of ~1900 m/s and an Isp of ~465 s for the LLV. To land 27 t of cargo and 4 crew on the lunar surface requires ~21.7 t of propellant

assuming a descent ΔV of ~2000 m/s. In the mission strategy adopted here, the LANTR LTV is loaded with an additional 10.9 t of LOX/LH$_2$ propellant that is transferred to the LLV after LOR to supplement its remaining 10.8 t propellant load. This "topping off" of the LLV's propellant tanks allows the crew and entire cargo shipment to be delivered to the surface on one round trip LLV mission. Included in the 27 t of surface payload is ~6.0 t of LH$_2$ propellant (~5 t) and tankage (~1 t) used by the LLV on its subsequent mission.

The reusable LANTR vehicle shown in Figure 6c operates at a MR = 3 (Isp ~647 s) both outbound and inbound, refuels with ~21.2 t of LUNOX for Earth return, and is a smaller overall vehicle than its expendable "all LH$_2$" counterpart, even with its increased performance. The LOX tank diameter and overall length are both 4.6 m and its capacity is ~65 t. The LH$_2$ tank is 7.6 m in diameter and 15 m in length but is only filled to ~85% of its maximum LH$_2$ capacity (~41.5 t) for this particular mission. The 15 m long tank is baselined here to provide commonality with a "36 hour" rapid cislunar nuclear shuttle discussed in the next section.

Compared to monopropellant NTRs, the LANTR engines are ~5% longer (an expansion ratio of 500 to 1 is used for improved LOX combustion efficiency) and ~6% heavier (attributed to the larger nozzle and the addition of the LOX propellant feed system). However, at MR = 3, the thrust output (F) from two 15 klbf LANTRs increases by 275% to ~82.5 klbf. This augmented thrust level significantly reduces the TLI burn duration and g-losses to 17.2 minutes and 72 m/s, respectively, compared to 47.5 minutes and 392 m/s for the "all LH$_2$" 30 klbf system. Total mission burn time is also cut in half to 28.9 minutes compared to 61.4 minutes for the expendable system. Because the LANTR engine lifetime is ~5 hours at a hydrogen exhaust temperature of ~2900 K (see Figure 4), the LANTR system can perform 10 round trip lunar missions before replacement thereby reducing LTS recurring costs.

The reusable LANTR has an IMLEO of ~151.8 t that includes the 17.5 t "dry" stage, a 10.7 t piloted LTV crew module, 22.0 t of non-propellant cargo, and RCS, LH$_2$, and LOX propellant loads of ~2.7, 34.5 and 65 t, respectively. During initial deployment, the entire LANTR LTV, including its RCS and LH$_2$ propellant loads, can be launched on a single SDV. The LOX tank would require on-orbit filling from an expendable propellant tanker or propellant depot. For subsequent piloted missions, the total mass needed to outfit and refuel the LTV stage is ~123.2 t and can again be launched on two 66 t-class SDVs.

Approximately 40.3 t of LUNOX (21.2 t for LTV return and 19.1 t for the LLV) must be produced to support each reusable mission. Automated, modular LUNOX production units and teleoperated mining equipment would be delivered to LLO by monopropellant and later LANTR systems, and then transported to the surface using on-board chemical propulsion. A 24 metric ton per year (t/year) LUNOX production unit based on hydrogen reduction of ilmenite (FeTiO$_3$) would have a total mass of ~17.3 t (Christiansen 1988), composed of an 80 kWe nuclear power system for continuous lunar day/night operation, equipment for mining, ilmenite beneficiation and processing. A single SDV could launch the entire production unit including its power system and lunar landing stage. Total plant mass and power requirements will vary of course with the LUNOX production rate increasing to 63.7 t and 485 kWe, respectively, for 6 modular units having a 144 t/year capacity (Christiansen 1988).

Rapid Cislunar Nuclear Shuttle

With LUNOX production underway and a reusable, LANTR LTV in service, the lunar outpost will expand to a permanent settlement staffed by visiting scientists and engineers representing both government and private commercial ventures. Convenient cislunar transportation, comparable to today's 24 hour flights from Washington, D.C. to Sydney, Australia, will make the Moon accessible to greater numbers of people and increase prospects for its commercial development. With the LANTR concept, one way flight times to and from the Moon of 36 to 24 hours appear possible with reasonable size vehicles and IMLEO values.

The ΔV requirements for TLI and LOI as a function of "one way" flight time are shown in Figure 7. For transit times less than 48 hours, the TLI and particularly the LOI ΔV requirements increase dramatically. The "free return" to Earth option of the Apollo program is no longer available, and the outbound trajectory is that of a hyperbolic Earth departure necessitating multiple spacecraft engines for passenger safety. The "ideal" TLI and LOI total ΔV requirement, for 24 and 36 hour transit times, are 6.9 and 5.1 km/s, respectively, compared to ~4.1 km/s for the 3.5 day reference lunar mission.
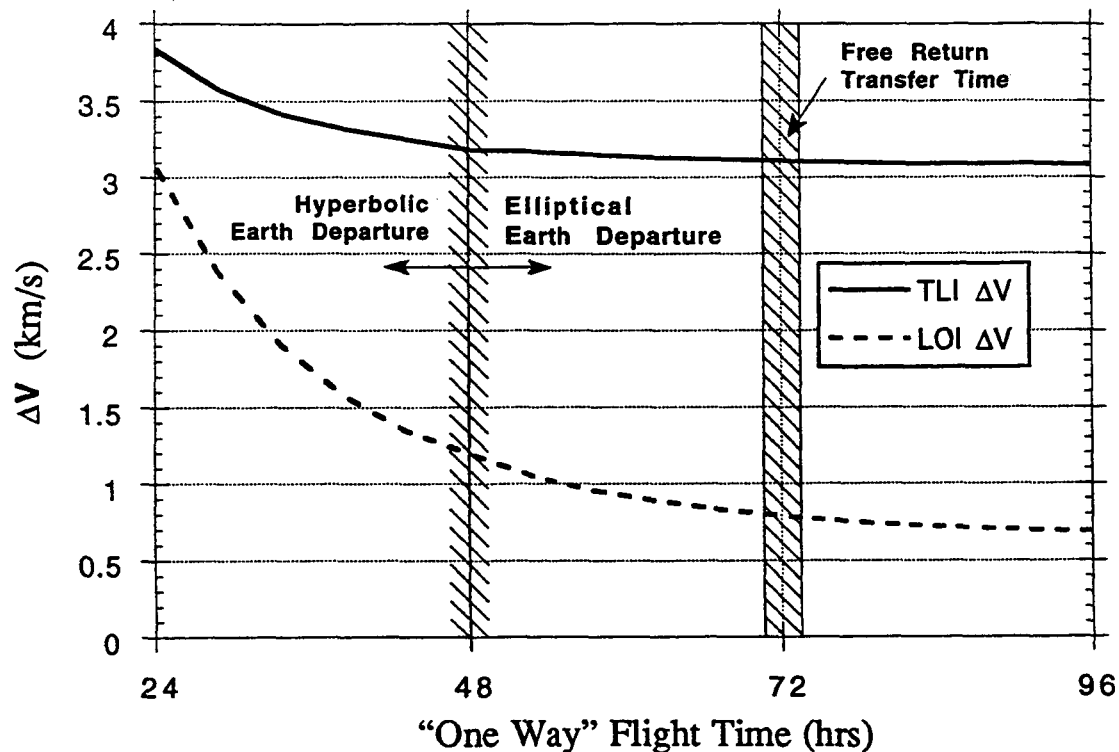
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FIGURE 7. TLI and LOI ΔV Variation With "One Way"
Flight Time (300 km Lunar Orbit).

A "36 hour" LANTR shuttle capable of transporting a 25 t passenger module to and from the Moon is shown in Figure 6d. It has an IMLEO of ~159 t, and is powered by two LANTR engines which produce 82.5 klbf of thrust using an outbound and inbound MR = 3. The spacecraft's LOX tank is 4.6 m in diameter and 4.9 m long and holds 70.5 t of Earth-supplied LOX required for the outbound trip. It is resupplied in LLO with 48.5 t of LUNOX for the 36 hour return trip to Earth. The LH₂ tank is 7.6 m in diameter and 15 m long and carries ~41.5 t of LH₂ required for the round trip mission. The mass breakdown of the LANTR shuttle includes the 20.5 t "dry" stage, a 25 t passenger module, and RCS, LH₂ and LOX propellant loads of 1.6, 41.4, and 70.4 t, respectively. Resupplying these propellant requirements for subsequent missions can again be easily accommodated within the 132 t lift capability of two 66 t-class SDVs. The total engine burn time for this mission is also attractive at ~45 minutes. Parametric data showing IMLEO variation with different outbound and inbound MR combinations for 36 and 24 hour "one way" trip times is shown in Figures 8 and 9, respectively.

Decreasing transit times from 36 to 24 hours increases ΔV and IMLEO requirements significantly by ~35% and 60%, respectively. A representative "24 hour" LANTR vehicle is shown in Figure 6e. Its two engines operate at an outbound MR = 4 (F ~96.9 klbf and Isp ~607 s) and an inbound MR = 6 (F ~121.8 klbf and Isp ~545 s). The shuttle's LOX tank is 4.6 m in diameter and ~9 m long and holds ~146 t of Earth-supplied LOX for the outbound lunar flight. It is resupplied in LLO with ~120 t of LUNOX for the 24 hour return trip to Earth. The LH₂ tank is 7.6 m in diameter and ~20.6 m in length (~3.1 m longer than the expendable NTR system's "core" tank) and carries ~59 t of LH₂ required for the round trip mission. The "24 hour" shuttle has an IMLEO of ~253.7 t that includes the 22.2 t "dry" vehicle, the 25 t passenger module, and RCS, LH₂ and LOX propellant loads of 2.0, 59.0 and 145.5 t, respectively. Total engine burn time for the "24 hour" mission is just under 64 minutes with the longest single burn being the TLI maneuver at ~29 minutes. The 27.4 m payload length limit of the Shuttle-derived launch vehicles assumed in this study determines the maximum allowable "core" stage LH₂ tank length and the corresponding outbound MR used here. While two SDV flights would be sufficient for deploying vehicle components, the initial and resupply propellant needs of the "24 hour" LANTR shuttle exceed their combined 132 t lift capability necessitating additional SDV launches. Excessive Earth-to-orbit launch costs could make shipment of LUNOX to LEO a commercial viable product for future high energy lunar missions.

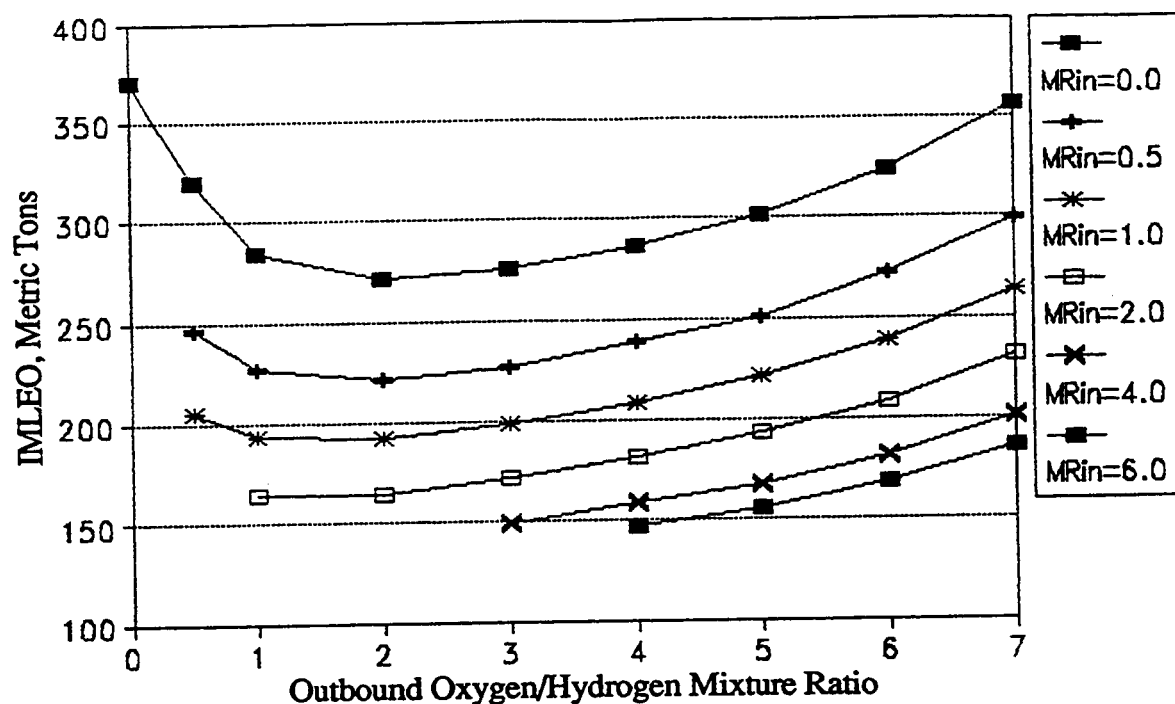9

25 Ton Passenger Module Both Ways, Resuable

FIGURE 8. Variation of IMLEO With O/H Mixture Ratio for "36 Hour" Lunar Transfer.
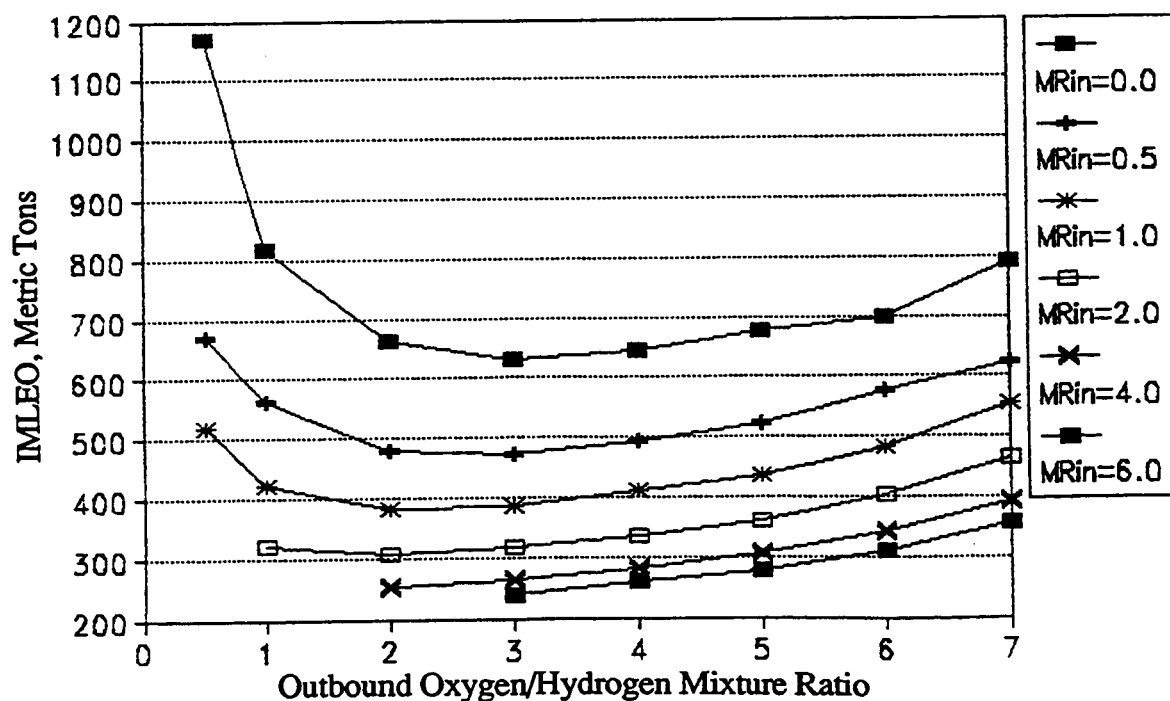
25 Ton Passenger Module Both Ways, Reusable

FIGURE 9. Variation of IMLEO With O/H Mixture Ratio for "24 Hour" Lunar Transfer.

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A possible scenario for a quick "commuter" trip to the Moon would start with airbreathing/scramjet SSTO transport of passengers to an international space station (ISS). There they would enter a short duration "passenger" module containing its own life support, I&C and auxiliary propulsion systems. The passenger module then departs the ISS and docks with a fully fueled LANTR shuttle awaiting it a safe distance away from the ISS. After a 24 to 36 hour transit to LLO, the passenger module detaches and docks with a waiting LLV (shown in Figure 10) for transport to the lunar surface. There it would be lowered to a "flat-bed" surface vehicle (see Figure 11) and transported to the lunar base air lock for docking and passenger unloading. Besides high energy lunar missions, the LANTR can also dramatically improve space transportation system performance wherever extraterrestrial sources of LOX and LH_2 can be acquired such as the Martian system, main-belt asteroids and the Galilean satellites Europa, Ganymede, and Callisto (Borowski et al. 1994).
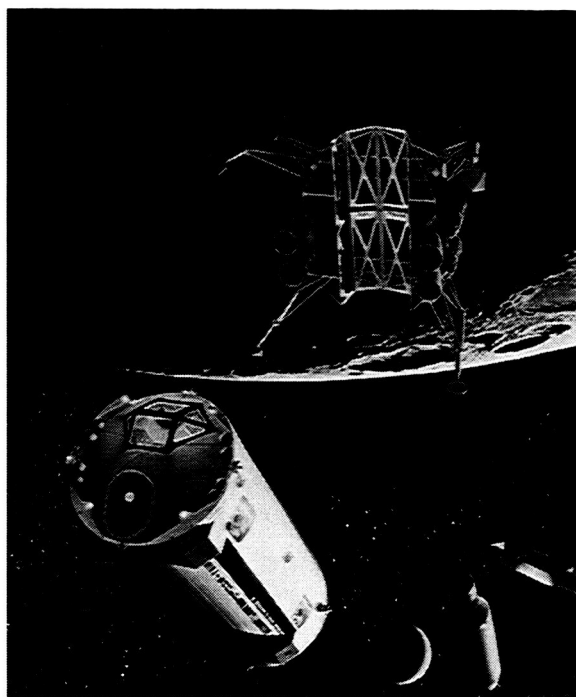

FIGURE 10. Artist's Illustration of "Commuter" Passenger Module Transferring From LANTR Stage to LLV in LLO.
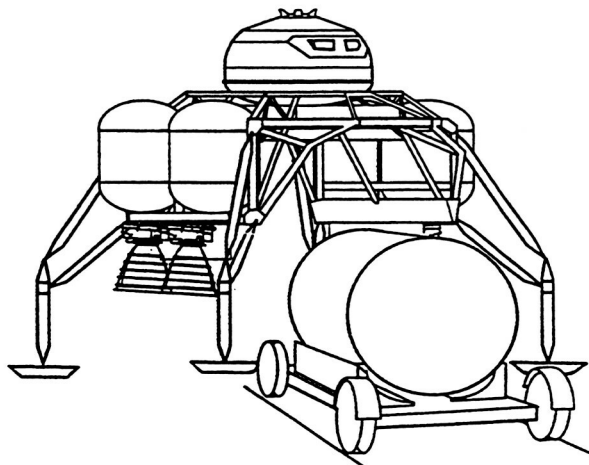

FIGURE 11. Surface Transport of Passenger Module to Lunar Base.

SUMMARY AND CONCLUSIONS

This paper describes operational characteristics and performance benefits of a versatile new engine concept--the LOX-augmented NTR. Combining conventional LH_2-cooled NTR and scramjet propulsion technologies in the form of a LOX "afterburner nozzle"and propellant feed system, the LANTR can operate at O/H mixture ratios up to MR = 7 resulting in a variable thrust and Isp capability. In the augmented thrust mode, clusters of small engines can provide "big engine" performance reducing engine development time and cost. The availability of LUNOX in LLO to "reoxidize" the LANTR enables reusable LTS operations with smaller, less massive LTVs having improved payload carrying capability compared to the "all LH_2" NTR systems. The LANTR can also provide quick "commuter" flights to and from the Moon with "one way" transit times on the order of 36 to 24 hours. The trimodal LANTR concept offers the potential for revolutionizing lunar space transportation and is expected to provide equally exciting prospects for the exploration of Mars and the outer solar system.

Acknowledgments

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13. ABSTRACT (Maximum 200 words)

An innovative trimodal nuclear thermal rocket (NTR) concept is described which combines conventional liquid hydrogen (LH_2)-cooled NTR, Brayton cycle power generation and supersonic combustion ramjet (scramjet) technologies. Known as the liquid oxygen (LOX)-augmented NTR (LANTR), this concept utilizes the large divergent section of the NTR nozzle as an "afterburner" into which LOX is injected and supersonically combusted with nuclear preheated hydrogen emerging from the LANTR's choked sonic throat--"scramjet propulsion in reverse." By varying the oxygen-to-hydrogen mixture ratio (MR), the LANTR can operate over a wide range of thrust and specific impulse (Isp) values while the reactor core power level remains relatively constant. As the MR varies from zero to seven, the thrust-to-weight ratio for a 15 thousand pound force (klbf) NTR increases by ~440%--from 3 to 13--while the Isp decreases by only ~45%--from 940 to 515 seconds. This thrust augmentation feature of the LANTR means that "big engine" performance can be obtained using smaller, more affordable, easier to test NTR engines. "Reoxidizing" the bipropellant LANTR system in low lunar orbit (LLO) with high density "lunar-derived" LOX (LUNOX) enables a reusable, reduced size and mass lunar transfer vehicle (LTV) which can be deployed and resupplied using two 66 t-class Shuttle-derived launch vehicles. The reusable LANTR can also transport 200 to 300% more payload on each piloted round trip mission than an expendable "all LH_2" NTR system. As initial outposts grow to eventual lunar settlements and LUNOX production capacity increases, the LANTR concept can also enable a rapid "commuter" shuttle capable of 36 to 24 hour "one way" trips to the Moon and back with reasonable size vehicles and initial mass in low Earth orbit (IMLEO) requirements.

14. SUBJECT TERMS

Nuclear thermal rocket; NTR; LUNOX; Lunar-oxygen; Scramjet cascade injector; LOX afterburner; "24 hour" lunar shuttle; LANTR

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